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Updated SCAA/ASPM Assessment of Gulf of Maine cod

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ABSTRACT

The ASPM (SCAA) assessments presented in Butterworth and Rademeyer (2008a) are updated through the addition of data for two more years, with the plus group extended from age 7 to age 8 on AIC grounds. Based largely on AIC considerations (though for technical reasons these are admittedly approximately calculated), the best assessment selected is that with a Ricker stock recruitment function and dome shaped selectivity. Amongst a number of sensitivity tests, an early gear change, use of the Baranov form rather than Pope's approximation, and commencing the assessment in different years (all prior to abundance index data becoming available) do not lead to any differences of note in estimates of key quantities. A simulation study shows the ASPM estimator to introduce only a slight bias towards a domed shape when the underlying reality exhibits asymptotically flat selectivities. Assessment variants which force flat selectivity in NEFSC surveys and the commercial fishery at large ages are not simply less preferred, but indeed strongly rejected under the AIC model selection criterion (e. g. relative AIC-weights of less than 10^{-13} for the standard M=0.2 specification). Such variants are not compatible with the low proportions of older cod in surveys and commercial catches – a feature for which cogent explanation needs to be offered before they might be accepted as providing a reliable basis for assessment. The greater rate of decline of commercial selectivity for old cod compared to that for the NEFSC surveys provides indirect confirmation of some dome effect, though further evidence from other sources would be desirable. The assessment can hardly distinguish different values of M, though increasing M above 0.2 suggests a lesser downward selectivity slope at large ages and a better resource status. Search over a range of stock recruitment relationships suggests the Ricker form to be preferred, though without completely eliminating the Beverton-Holt form in AIC terms. Under the best assessment, the stock is estimated at present to be at some 80% of its MSY level in terms of spawning biomass, with most variants suggesting somewhat higher levels than this.

REFERENCE POINT SUMMARY

	Ricker	Beverton-Holt
B^{sp}_{2006}	43	43
B^{sp}_{MSY}	53	33
$B^{sp}_{2006}/ B^{sp}_{MSY}$	0.81	1.30
F_{2006}	0.17	0.18
F_{MSY}	0.46	0.58

Note: Biomass units are '000 tons; F refers to age 5 where the commercial selectivity peaks.

INTRODUCTION

This paper reports revised and updated assessment results for the Gulf of Maine cod to those presented in Butterworth and Rademeyer (2008a) to the previous GARM held in February 2008. It further addresses a number of questions raised at that GARM in relation to those earlier results. A 2007 Reference Case ASPM (SCAA) assessment is developed, and the results for various sensitivities to this are also reported. The paper concludes with a summary discussion of key findings.

DATA AND METHODOLOGY

Differences in data and methodologies to those used in Butterworth and Rademeyer (2008a) are detailed in Appendix A. In essence the data used have been extended by two years to end in 2007 rather than in 2005. The specifications for the ASPM assessment methodology are unchanged, except that for reasons elaborated in Appendix A, the plus group for catch-at-age data for both commercial catches and NEFSC surveys as fit in the ASPM assessments is taken to be 8+ instead of 7+. Because of time constraints, estimates of precision have been reported approximately in the form of Hessian-based CV's, rather than as Bayesian-based 95% probability intervals as in Butterworth and Rademeyer (2008a).

During the last GARM, suggestions were made that the ASPM estimator used might be biased, in the direction that even though underlying selectivities were asymptotically flat, an estimator that allowed for the possibility of a dome shape (i.e. decreasing selectivity with age at older ages) would tend to provide selectivity estimates that were indeed decreasing in this manner. To investigate this, a simulation evaluation was conducted using for an operating model the ASPM assessment for the 2007 Reference Case described below, except with the modification that selectivities were forced to be flat for ages 5 and above for the commercial fishery, and ages 6 and above for the NEFSC surveys. This operating model was used to generate 100 pseudo data sets, each identical in form to those used for the assessment, except that errors were added to the expected values for the annual abundance indices and catch at age data in accordance with the distributions assumed for these by the likelihood adopted for the ASPM estimator, and with variances as estimated in the original fit of this operating model to the abundance indices. Some slight modifications were however made to this formulation for generating the pseudo catch at age proportions: first variances were not estimated from the unadjusted residuals of the fit, since these showed bias, so that instead these variances were recalculated relative to the average value of these residuals; secondly, errors added to provide the pseudo data were generated to be mean rather than median unbiased, since without this correction such bias can be large for some of the ages for which the expected proportions in the catch are low given the log-normal distributional form being used; and finally, after generating residuals from these lognormal distributions to add to the expected values, the resultant pseudo proportions for each year were rescaled to ensure that they summed to 1. The Reference Case ASPM estimator, with selectivities at larger ages than 5 for the commercial fishery and 6 for the NEFSC surveys freely estimable (and not even restricted to be 1 or less) was then applied to each of the 100 pseudo data sets to determine the (effectively parametric bootstrap) distributions for quantities of interest, including particularly the selectivities at large ages, to determine whether there was any evidence for the bias suggested in circumstances corresponding to assessment under consideration.

RESULTS

Reference Case ASPM

For reasons given in the summary discussion section following (as they relate also to the results for some of the sensitivity tests following), the Reference Case ASPM variant chosen for the updated assessment is of the same form as adopted in Butterworth and Rademeyer (2008a). Important aspects of this choice are those of a Ricker form for the stock-recruitment relationship, and a lack of constraints (specifically that of asymptotic flatness) on the estimation of selectivities at larger ages for both the commercial fishery and the NEFSC surveys.

Results for this 2007 Reference Case (RC) are reported as Case 1 in Table 1, with the associated spawning biomass (B^{sp}) trajectory shown in Fig. 1. The fits to the abundance indices are shown in Fig. 2, and those to the catch at age proportions in Figs 3 and 4; the selectivities estimated are shown in Fig. 5, and the estimated stock-recruitment relationship is plotted in Fig. 6 together with point estimates and (log) residuals about the relationship for the period 1956-2006 (for which the available catch at age proportion data from the surveys and fishery contain some information on recruitment variation).

Comparison of results for this RC to the previous 2005 Reference Case (shown as Case 0 in Table 1) are slightly confounded by the different choice for the plus-group age. However the comparative plots of B^{sp} in Fig. 1 show very little difference over recent years. B^{sp} has generally been increasing since the late 1990s, with the current level now about double that at that low point, and approaching MSYL (i.e. $B^{sp}\big/B^{sp}_{MSY}$ is approaching 1). Retrospective plots are shown in Fig. 7, and do not indicate any appreciable systematic pattern.

ASPM Sensitivities

a) Early NEFSC gear change

For Sensitivity 2, account is taken of a change in gear over the 1973-1981 period by assuming a different catchability coefficient q for the NEFSC spring survey during that time (similarly to what was done in Butterworth and Rademeyer, 2008b). This does result in an improvement in the likelihood that would justify the modification in AIC terms. However, it is unclear whether modifying q alone would be sufficient to account for this gear change, and importantly changes in estimates of current resource status reflect only slight improvements compared to the RC (by "status", reference is intended in particular to values of current spawning biomass $B^{sp}{}_{2006}$ in absolute terms and as a proportion of MSYL: $B^{sp}{}_{2006}/B^{sp}{}_{MSY}$). Hence the RC was not changed to include this adjustment.

b) Baranov equation in place of Pope approximation

Sensitivity 3 in Table 1 shows the results of replacing Pope's approximation by the Baranov catch equation in the formulae for the resource dynamics. The resultant differences are not large, and only barely evident in the comparative plots of B^{sp} as shown in Fig.1. Thus although a notable improvement in the likelihood compared to the RC is obtained (see Table 1), because of the increased computational burden (which would also render Bayesian PI estimation infeasible), Pope's approximation has been retained.

c) Selectivity slopes at larger ages

Sensitivities to changes in assumptions regarding selectivities at large ages involve allowing for different slopes in spring and autumn NEFSC surveys (Sensitivity 4), and forcing flat selectivity at ages of 6 and above for these surveys and then also for the commercial fishery as well for ages of 5 and above (Sensitivities 5a and 5b respectively). Results are reported in Table 1 with the different selectivities consequently estimated shown in Fig. 5.

Sensitivity 4 indicated a slightly faster fall off in selectivity for the spring than the winter survey, though the small improvement in likelihood is insufficient to justify the addition of two further estimable parameters.

Results for Sensitivities 5a and 5b show that when the NEFSC survey selectivities are assumed to be asymptotically flat, the commercial selectivity is estimated to be dome shaped (decreasing after age 5, see Fig. 5). The associated addition of additional three estimable parameters for the commercial selectivity (compared to assuming this flat as for Sensitivity 5b) marginally fails to be AIC justified, though the results suggest that this conclusion would be reversed given a more parsimonious parametrization of this decline relative to the surveys.

The major difference associated with these flat selectivity assumptions is the substantial deterioration in model fit: a log likelihood deterioration nearing 60, or a corresponding AIC deterioration of about 107, for Sensitivity 5b with flat selectivities for both the commercial fishery and the NEFSC surveys compared to RC. This is a larger difference than for the 2005 Reference Case in Butterworth and Rademeyer (2008a), for which the flat selectivity assumption resulted in an AIC deterioration of about 60. The reason for this deterioration relates to the fit to the catch at age proportions, particularly for larger ages, and especially for the NEFSC autumn surveys which catch substantially less 8+ fish than predicted under a flat selectivity assumption (see Figs 8 and 9). Fig. 10 compares the residuals for these fits for ages 7 and 8+ for Sensitivity 5b and the RC.

Fig. 1 compares the B^{sp} trends under these different selectivity assumptions. Forcing flat selectivity reduces the biomass estimated in absolute terms, but the corresponding estimate of pristine biomass K^{sp} is reduced further, with the net result that the resource is estimated to now be above MSYL. Fig. 11 shows the estimated stock-recruitment curve (with associated point estimates for 1956-2006) for Sensitivity 5b, and compares this to the curve estimated for the RC.

d) Different prescriptions for M

Sensitivity 6a increases the assumed age-independent value of 0.2 yr^{-1} for *M* in the RC to 0.3, while Sensitivites 6b and 6c allow *M* to decrease with age *a* according to:

$$M_a = \begin{cases} M_2 & a = 1 \\ \alpha_1 + \dfrac{\alpha_2}{a+1} & 2 \le a \le 10 \\ M_{10} & a = 11+ \end{cases}$$

where the parameters α_1 and α_2 are chosen so than *M* ranges from 0.4 to 0.1 over ages 2 to 10 for Sensitivity 6b, and 0.3 to 0.15 for Sensitivity 6c (see Table 1). B^{sp} trends are compared in Fig. 1, and estimated NEFSC spring and commercial selectivities in Fig. 12.

For *M*= 0.3, the likelihood is marginally improved. The population is estimated to be above MSYL, primarily because the estimated K^{sp} is much lower than for the RC, and the extent of selectivity dome is less pronounced (i.e. the *slope* estimates reduce – see Table 1).

With *M* age dependent, results for the lesser extent (Sensitivity 6c) differ little from the RC. For the greater variation case (Sensitivity 6b), stock status as indicated by $B^{sp}_{2006} / B^{sp}_{MSY}$ is notably worse (probably because the lower *M* at large ages means slower dynamics and hence a longer time needed for recovery), but the likelihood shows notable deterioration. However, a particular reason for adding Sensitivities 6b and 6c was that a reviewer at the previous GARM suggested that the (quite plausible) possibility of *M* actually decreasing with age *a* could lead to a mistaken conclusion of dome shaped selectivity if the assessment assumed age-independent *M*. In fact the reverse is true – the estimated selectivity slopes increase under the assumption of *M* decreasing with age to less than the constant *M* = 0.2 of the RC, making the dome shape more marked – see Table 1 and Fig. 12). This occurs because *given* the observed proportions at age, if *M* at large age in set lower, so that mortality effects do not reduce the proportion of fish present as fast as age increases, then selectivity has to drop yet faster to account for the lowish catches made of these older fish.

e) Different stock-recruitment relationships

Sensitivities 7, 8 and 9, for which results are shown in Table 2, all relate to aspects of the stock-recruitment relationship which is internally estimated in an ASPM assessment approach. Fig. 13 compares the associated estimated stock-recruitment curves with that for the RC.

Sensitivity 7 considers different values for the γ parameter of the generalised Ricker stock-recruitment relationship considered:

$$R_y = \alpha B^{sp}_{y-1} \exp\left[-\beta \left(B^{sp}_{y-1}\right)^{\gamma}\right] e^{(\varsigma_y - (\sigma_R)^2/2)}$$

(see equation A2.4 of Butterworth and Rademeyer (2008a)), for which the RC selects γ = 1 corresponding to the conventional Ricker form. Comparative B^{sp} plots for different values of γ in Fig. 1 show little difference in recent years. As the value of γ is reduced below 1, the stock-recruitment curve takes on a shape closer to that of the Beverton-Holt form (see Fig. 13) and estimated values of $B^{sp}_{2006}/B^{sp}_{MSY}$ increase to above 1. However, the likelihood deteriorates, and the best fit is found (Sensitivity 7a) for γ = 1.19 (i.e a steeper drop in recruitment at large B^{sp} than for Ricker), though the improvement in likelihood compared to the RC is marginal and insufficient to justify treating γ as an estimable parameter.

Sensitivity 8 addresses lessening the weight given to the fit to the stock-recruitment curve in the overall assessment, while Sensitivity 9 replaces the Ricker by the Beverton-Holt form. The former is effected by increasing the value of the σ_R parameter which reflects the extent of the variation of recruitment about the stock-recruitment curve. For both forms, increasing σ_R to 1.0 results in a decrease in the estimate of $B^{sp}_{2006}/B^{sp}_{MSY}$ compared to the RC choice of σ_R, = 0.4, but since neither RC fit shows any evidence of model mis-specification (see Figs 6 and 11) and reflects (log) residuals with a standard deviation of about 0.5, there seems little justification to decrease weighting in this way.

The Beverton-Holt equivalent of the RC (Sensitivity 9a) shows recent B^{sp} trends that are scarcely distinguishable from those for the Ricker form of the RC (see Fig. 1). The key difference is that pristine abundance K^{sp} is estimated to be about 35% higher for Beverton-Holt than for Ricker, but this is more than offset by the estimate of B^{sp}_{MSY}/K decreasing from 0.36 to 0.16, so that for the Beverton-Holt form the resource is estimated to be appreciably above MSYL at present. The Ricker form is however preferred in terms of likelihood (a –ln$L$ improvement of about 4, or about 8 in AIC terms).

If the Beverton-holt form is assumed *in conjunction* with forcing asymptotically flat selectivity (Sensitivity 9c), current resource status is estimated to be appreciably lower than for the RC, both in absolute B^{sp} terms and relative to MSYL, but –ln$L$ is again considerably worse than for the RC by about 33 (an AIC difference of about 58). However, within the constraint of such a flat selectivity assumption, the Beverton-Holt result becomes preferred to that for the Ricker form in likelihood terms.

Fig. 14 show plots requested by reviewers at the previous GARM for B^{sp} trajectories under the assumption of a zero catch throughout the period considered in the assessment, but assuming that the same series of recruitments had occurred. These are shown for both the RC and its equivalent with the Ricker replaced by a Beverton-Holt stock-recruitment function. The reason for the initial upward hump in the Ricker case is that when catches reduce spawning biomass below the K^{sp} level assumed for 1893 for the RC, the Ricker form responds by increasing recruitment.

f) Different starting years

Table 3 provides results for alternative starting years (than 1893 for the RC) for the ASPM assessments. These are motivated by concerns about the accuracy of total commercial catch records for earlier years. Results are shown for alternative specifications for both B^{sp} as a fraction of K^{sp} and for the (non-pristine) age structure of the population in the starting year.

Alternative starting years of 1930 and 1960 are considered (thus both reflect choices prior to the commencement of the NEFSC surveys). Estimates of $B^{sp}_{2006} \big/ B^{sp}_{MSY}$ generally differ little from that for the RC, indicating that transient effects related to specifications for the start year chosen for the assessment (certainly if this is before survey data started to become available) have died out well before the turn of the century and would hardly impact estimates of quantities of current management relevance.

Possible bias in estimation of selectivity at large ages

The results of the simulation evaluation into the possibility that the ASPM estimator used for the RC assessment introduces bias, in the sense of being likely to lead to the inference of dome shaped selectivity even when the underlying fishing and survey selectivities are asymptotically flat, are reported in Table 4 and Fig. 15.

Table 4 provides no real indication of such bias in estimated selectivities out to age 7. There is a drop on average in the selectivities estimated for age 8 for both the NEFSC surveys and the commercial fishery, but this is small compared to the estimates for the actual RC (see Fig. 5). Corresponding to that drop, there is a slight positive bias in estimates of B^{sp} in absolute terms, but this is negligible when expressed relative to estimates of K^{sp} (see Fig. 15). and similarly there is little indication of bias in the estimate of current resource status $B^{sp}_{2006} \big/ B^{sp}_{MSY}$ (Table 4).

SUMMARY DISCUSSION

Preferences expressed amongst alternative assessments presented in this paper have broadly been based on likelihood/AIC based model selection criteria. Amongst the more important factors under consideration, the Ricker form for the stock-recruitment relationship shows an AIC improvement of about 8 compared to the Beverton-Holt, while allowing for domed shaped rather than asymptotically flat selectivity improves AIC by over 100. Alternatives to the M= 0.2 independent of age assumption achieve little in AIC terms, and some other changes, while perhaps justifiable in terms of AIC, make little difference to estimates of the current status of the stock.

These considerations are what led to the choice of the Ricker/domed selectivity/M = 0.2 ASPM variant as the Reference Case, and indeed this seems the most appropriate result to advance if a single “best assessment” choice is to be made. It reflects a current spawning biomass that is some 80% of MSYL, and most alternatives estimate this status to be better still, in some cases even exceeding MSYL. The one notable exception is the combination of flat selectivity with a Beverton-Holt stock-recruitment form, but the AIC for this is less than that for the RC by an appreciable amount of almost 60.

The question of whether or not selectivity is domed shaped is probably the most important to address in reaching a conclusion about the current status of the Gulf of Maine cod population. The simulation evaluations reported above indicate that any estimator bias can at best account for only a small proportion of the decreasing selectivity estimated at large ages. A higher natural mortality than the RC assumption of M = 0.2

would reduce but not eliminate this trend (assuming M was kept within a realistic biological range), though would also suggest an improved status for the resource in terms of $B^{sp}_{2006}/B^{sp}_{MSY}$.

In terms of AIC, the preference for domed over asymptotically flat selectivity is much stronger than that for a Ricker over Beverton-Holt stock-recruitment curve. While for reasons discussed in Butterworth and Rademeyer (2008a) (the use of penalty terms in the likelihood, and probable non-independence amongst the data fitted), one must take care against over-interpreting the AIC values quoted above, they nevertheless provide some broad guidance on relative model plausibility. One needs to consider AIC differences of over 100 for a Ricker form, or approaching 60 for Beverton-Holt, if selectivity is forced to be asymptotically flat, in the context of statements by Burnham and Anderson (1998) that an AIC difference exceeding 4 indicates that a model is not highly plausible, and one over 10 provides strong evidence that a model is not competitive. The issue in this case is not simply one of preference under a model selection criterion, but of how quantitatively strong that preference is (e.g. under AIC-weighting, the relative weight given to flat vs domed selectivity models would be better for Beverton-Holt at some e^{-30}, or about 10^{-13}, which is negligible. Fundamentally, flat selectivity models are statistically incompatible with the low proportions of older fish in the fishery and surveys. These models cannot provide a defensible basis for inference unless linked to some related plausible hypothesis about model or data errors (systematic bias in ageing perhaps?).

Nonetheless care also has to be taken with dome shaped selectivity conclusions from a management perspective, as they imply a “cryptic” biomass of older fish in the system, which for reasons probably linked to emigration out of the fishing area or net avoidance, are not available to the fishery. Fig. 16 shows the relative size of this “missing” proportion, which is bigger by mass than by number. Independent of the purely statistical arguments, there are some indications that emigration effects at least are playing some role in this case. These are provided by the differences in estimates of selectivity at large ages between the NEFSC summer and autumn surveys, and the steeper decline in selectivity for the commercial fishery compared to these surveys (see Fig. 5 and Sensitivities 4, 5a and 5b in Table 1). Though the evidence for the first of these effects is weak and distinguishing the two surveys in this way is not justified in AIC terms, the evidence for the second is considerably stronger, and certainly raises questions about justification for the assumption of asymptotically flat selectivity in VPA-based assessments. Clearly information on this issue from other sources, such as tag-recapture studies, would be welcome.

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Table 1: Penalised maximum likelihood estimates of key management quantities for the 2005 Reference Case ASPM (Butterworth and Rademeyer (2007), the 2007 Reference Case and sensitivities thereto. Biomass units are thousand tons. The estimates given for quantities such as B^{sp}_{MSY} refer to the commercial selectivity function from 1992+. The *slope* statistic is $-\ln(S_8/S_7)$. Values shown in bold are fixed on input. Values in parenthesis are Hessian-based CV's. Values of –ln$L$ shown in square parenthesis [ ] are not comparable to those for the 2007 Reference Case.

	0		1		2		3		4		5a		5b		6a		6b		6c	
	2005 Reference Case		2007 Reference Case		Earlier NEFSC survey q change		Using Baranov		Different survey slopes		Flat selectivity (survey only)		Flat selectivity (commercial and survey)		M=0.3		M age dependent (0.4-0.1)		M age dependent (0.35-0.15)	
-lnL	[-46.29]		8.34		6.00		3.83		7.87		64.23		66.94		7.92		12.77		8.25	
M	**0.20**	-	**0.20**	-	**0.20**	-	**0.20**	-	**0.20**	-	**0.20**	-	**0.20**	-	**0.30**	-	**0.4 - 0.1**	-	**0.35-0.15**	-
h	1.67	(0.16)	1.34	(0.15)	1.36	(0.15)	1.48	(0.15)	1.32	(0.15)	2.75	(0.04)	2.85	(0.03)	1.13	(0.16)	1.46	(0.16)	1.46	(0.16)
γ	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-
K^{sp}	127.32	(0.11)	147.31	(0.10)	146.10	(0.10)	134.49	(0.10)	149.36	(0.10)	80.78	(0.04)	76.89	(0.01)	93.34	(0.11)	224.55	(0.14)	162.41	(0.12)
$B^{sp}{}_{2004}$	37.14	(0.14)	34.49	(0.14)	35.57	(0.14)	31.61	(0.13)	35.23	(0.14)	23.42	(0.11)	22.35	(0.10)	31.41	(0.12)	38.22	(0.20)	34.46	(0.15)
$B^{sp}{}_{2006}$			42.87	(0.15)	44.56	(0.15)	40.15	(0.14)	43.63	(0.15)	31.96	(0.13)	30.55	(0.12)	38.47	(0.13)	47.71	(0.20)	43.79	(0.15)
$B^{sp}{}_{2004}/K$	0.29	(0.13)	0.23	(0.13)	0.24	(0.14)	0.24	(0.13)	0.24	(0.13)	0.29	(0.11)	0.29	(0.10)	0.34	(0.14)	0.17	(0.12)	0.21	(0.13)
$B^{sp}{}_{2006}/K$			0.29	(0.15)	0.30	(0.16)	0.30	(0.16)	0.29	(0.15)	0.40	(0.13)	0.40	(0.13)	0.41	(0.16)	0.21	(0.14)	0.27	(0.15)
$B^{sp}{}_{MSY}$	46.90	(0.08)	53.05	(0.09)	52.51	(0.09)	47.55	(0.09)	53.90	(0.09)	30.13	(0.05)	29.50	(0.02)	35.41	(0.07)	77.97	(0.09)	56.85	(0.09)
$B^{sp}{}_{2004}/B^{sp}{}_{MSY}$	0.79	(0.15)	0.65	(0.15)	0.68	(0.15)	0.66	(0.14)	0.65	(0.14)	0.78	(0.11)	0.76	(0.11)	0.89	(0.14)	0.49	(0.16)	0.61	(0.15)
$B^{sp}{}_{2006}/B^{sp}{}_{MSY}$			0.81	(0.15)	0.85	(0.15)	0.84	(0.15)	0.81	(0.15)	1.06	(0.13)	1.04	(0.13)	1.09	(0.14)	0.61	(0.16)	0.77	(0.15)
$B^{sp}{}_{MSY}/K$	0.37	(0.13)	0.36	(0.13)	0.36	(0.13)	0.35	(0.14)	0.36	(0.13)	0.37	(0.04)	0.38	(0.03)	0.38	(0.15)	0.35	(0.10)	0.35	(0.14)
MSY	13.40	(0.05)	12.54	(0.06)	12.61	(0.06)	12.82	(0.06)	12.45	(0.06)	13.83	(0.02)	13.64	(0.01)	11.81	(0.06)	11.15	(0.04)	12.12	(0.06)
F_{MSY}	0.62	-	0.46	-	0.46	-	0.50	-	0.45	-	0.59	-	0.54	-	0.53	-	0.41	-	0.47	-
$F_{2004/2006}$	0.26	(0.16)	0.17	(0.15)	0.17	(0.15)	0.19	(0.15)	0.17	(0.15)	0.15	(0.14)	0.15	(0.14)	0.17	(0.14)	0.20	(0.16)	0.18	(0.15)
Comm *slope*	0.28	(0.59)	0.57	(0.18)	0.57	(0.18)	0.59	(0.18)	0.58	(0.18)	0.09	(1.08)	**0.00**	-	0.37	(0.31)	0.72	(0.15)	0.63	(0.16)
NEFSC *slope*	0.26	(0.14)	0.47	(0.10)	0.47	(0.10)	0.46	(0.10)	0.46	(0.13)	**0.00**	-	**0.00**	-	0.25	(0.20)	0.68	(0.07)	0.54	(0.08)
									0.47	(0.12)										

Table 2: Penalised maximum likelihood estimates of key management quantities for the 2007 Reference Case ASPM and seven sensitivities related to the stock-recruitment relationship. Biomass units are thousand tons. The estimates given for quantities such as B^{sp}_{MSY} refer to the commercial selectivity function from 1992+. The *slope* statistic is $-\ln(S_8/S_7)$. Values shown in bold are fixed on input. Values in parenthesis are Hessian-based CV's. Values of –ln*L* shown in square parenthesis [] are not comparable to those for the 2007 Reference Case.

			Different values for gamma						Different values for σ_R				Beverton-Holt SR with different values of σ_R					
	1		7a		7b		7c		8a		8b		9a		9b		9c	
	2007 Reference Case		γ estimated		γ=0.50*		γ=0.25		σ_R=0.5		σ_R=1		σ_R=0.4		σ_R=1.0		σ_R=0.4, flat comm and survey sel	
-lnL	8.34		8.25		9.56		10.93		[-7.00]		[-28.37]		12.47		[-27.64]		41.35	
M	**0.20**	-	**0.20**	-	**0.20**		**0.20**	-	**0.20**	-	**0.20**	-	**0.20**	-	**0.20**	-	**0.20**	-
h	1.34	(0.15)	1.36	(0.24)	1.27		1.15	(0.09)	1.47	(0.18)	1.78	(0.22)	0.95	(0.10)	0.98	*	0.90	(0.00)
γ	**1.00**	-	1.19	-	**0.50**		**0.25**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-
K^{sp}	147.31	(0.10)	142.50	(0.16)	163.10		176.78	(0.07)	139.33	(0.12)	151.71	(0.21)	201.88	(0.11)	263.43	(0.15)	147.53	(0.00)
B^{sp}_{2004}	34.49	(0.14)	34.27	(0.15)	35.48		35.52	(0.14)	32.28	(0.14)	29.65	(0.16)	35.31	(0.15)	31.50	(0.16)	15.86	(0.21)
B^{sp}_{2006}	42.87	(0.15)	42.67	(0.15)	43.78		43.52	(0.14)	40.58	(0.15)	38.10	(0.17)	42.73	(0.16)	39.69	(0.17)	19.30	(0.34)
B^{sp}_{2004}/K	0.23	(0.13)	0.24	(0.14)	0.22		0.20	(0.12)	0.23	(0.14)	0.20	(0.19)	0.17	(0.14)	0.12	(0.15)	0.11	(0.21)
B^{sp}_{2006}/K	0.29	(0.15)	0.30	(0.17)	0.27		0.25	(0.13)	0.29	(0.16)	0.25	(0.22)	0.21	(0.15)	0.15	(0.16)	0.13	(0.34)
B^{sp}_{MSY}	53.05	(0.09)	54.84	(0.09)	44.93		40.55	(0.08)	49.62	(0.09)	59.33	(0.19)	32.80	(0.12)	39.46	(0.18)	37.08	(0.02)
$B^{sp}_{2004}/B^{sp}_{MSY}$	0.65	(0.15)	0.62	(0.17)	0.79		0.88	(0.13)	0.65	(0.15)	0.50	(0.20)	1.08	(0.14)	0.80	(0.16)	0.43	(0.19)
$B^{sp}_{2006}/B^{sp}_{MSY}$	0.81	(0.15)	0.78	(0.16)	0.97		1.07	(0.14)	0.82	(0.16)	0.64	(0.20)	1.30	(0.14)	1.01	(0.17)	0.52	(0.32)
B^{sp}_{MSY}/K	0.36	(0.13)	0.38	(0.19)	0.28		0.23	(0.09)	0.36	(0.15)	0.39	(0.19)	0.16	(0.14)	0.15	(0.07)	0.25	(0.02)
MSY	12.54	(0.06)	12.96	(0.09)	11.40		10.73	(0.05)	13.00	(0.07)	16.70	(0.16)	9.92	(0.09)	13.71	(0.14)	8.64	(0.01)
F_{MSY}	0.46	-	0.46	-	0.49		0.51	-	0.49	-	0.51	-	0.58	-	0.63	-	0.22	-
F_{2006}	0.17	(0.15)	0.18	(0.15)	0.17		0.18	(0.14)	0.18	(0.16)	0.19	(0.17)	0.18	(0.15)	0.19	(0.16)	0.26	(0.37)
Comm *slope*	0.57	(0.18)	0.57	(0.20)	0.58		0.59	(0.18)	0.56	(0.19)	0.55	(0.20)	0.60	(0.17)	0.58	(0.18)	**0.00**	-
NEFSC *slope*	0.47	(0.10)	0.47	(0.11)	0.48		0.48	(0.10)	0.46	(0.10)	0.44	(0.12)	0.48	(0.10)	0.47	(0.10)	**0.00**	-

* Hessian based CV's not available as ADMB struggled to converge to minimum.

Table 3: Penalised maximum likelihood estimates of key management quantities for the 2007 Reference Case ASPM and four sensitivities with different starting years and θ and ϕ parameters. (Note: θ is the B^{sp}/K^{sp} value in the starting year; ϕ is added to M to provide a starting age-structure. Biomass units are thousand tons. The estimates given for quantities such as B^{sp}_{MSY} refer to the commercial selectivity function from 1992+. The *slope* statistic is $-\ln(S_8/S_7)$. Values shown in bold are fixed on input. Values in parenthesis are Hessian-based CV's.

			Different combination of starting year and θ parameter											
			Start year 1930						Start year 1960					
	1		10a		10b		10v		11a		11b		11c	
	2007 Reference Case		θ=0.8, ϕ=0.4		θ=0.5, ϕ=0.4		θ=0.2, ϕ=0.4		θ=0.8, ϕ=0.4		θ=0.5, ϕ=0.4		θ=0.2, ϕ=0.4	
-lnL	8.34		7.79		7.87		7.02		34.25		15.33		15.81	
M	**0.20**	-	**0.20**	-	**0.20**	-	**0.20**	-	**0.20**	-	**0.20**	-	**0.20**	-
h	1.34	(0.24)	1.32	(0.13)	1.35	(0.13)	1.41	(0.14)	0.85	(0.12)	1.30	(0.15)	1.41	(0.16)
γ	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-	**1.00**	-
K^{sp}	147.31	(0.16)	136.32	(0.13)	134.69	(0.12)	131.34	(0.10)	213.63	(0.11)	145.60	(0.13)	118.87	(0.17)
B^{sp}_{2004}	34.49	(0.15)	32.49	(0.15)	32.11	(0.14)	33.76	(0.14)	55.42	(0.13)	41.55	(0.14)	26.94	(0.16)
B^{sp}_{2006}	42.87	(0.15)	40.21	(0.16)	39.90	(0.15)	41.88	(0.15)	63.17	(0.14)	50.04	(0.15)	33.92	(0.16)
B^{sp}_{2004}/K	0.23	(0.14)	0.24	(0.13)	0.24	(0.13)	0.26	(0.13)	0.26	(0.12)	0.29	(0.13)	0.23	(0.13)
B^{sp}_{2006}/K	0.29	(0.17)	0.29	(0.15)	0.30	(0.15)	0.32	(0.15)	0.30	(0.13)	0.34	(0.14)	0.29	(0.16)
B^{sp}_{MSY}	53.05	(0.09)	49.23	(0.12)	48.53	(0.11)	46.95	(0.09)	80.73	(0.13)	52.26	(0.11)	43.06	(0.12)
$B^{sp}_{2004}/B^{sp}_{MSY}$	0.65	(0.17)	0.66	(0.14)	0.66	(0.14)	0.72	(0.14)	0.69	(0.17)	0.80	(0.15)	0.63	(0.13)
$B^{sp}_{2006}/B^{sp}_{MSY}$	0.81	(0.16)	0.82	(0.15)	0.82	(0.15)	0.89	(0.15)	0.78	(0.17)	0.96	(0.15)	0.79	(0.15)
B^{sp}_{MSY}/K	0.36	(0.19)	0.36	(0.11)	0.36	(0.12)	0.36	(0.13)	0.38	(0.15)	0.36	(0.15)	0.36	(0.12)
MSY	12.54	(0.09)	11.46	(0.08)	11.59	(0.08)	11.73	(0.05)	10.54	(0.11)	11.64	(0.09)	10.97	(0.07)
F_{MSY}	0.46	-	0.45	-	0.46	-	0.48	-	0.35	-	0.48	-	0.44	-
F_{2006}	0.17	(0.15)	0.18	(0.15)	0.18	(0.15)	0.18	(0.15)	0.17	(0.15)	0.17	(0.15)	0.20	(0.16)
Comm *slope*	0.57	(0.20)	0.59	(0.18)	0.57	(0.18)	0.58	(0.17)	0.69	(0.15)	0.62	(0.17)	0.51	(0.22)
NEFSC *slope*	0.47	(0.11)	0.47	(0.10)	0.46	(0.10)	0.47	(0.10)	0.56	(0.08)	0.49	(0.09)	0.35	(0.17)

Table 4: Median and 90% PI's for distributions of estimates of NEFSC survey selectivity, ages 7 and 8, commercial selectivity, ages 6 to 8, and $B^{sp}_{2006} \big/ B^{sp}_{MSY}$ under the application of an estimator identical to the RC assessment which allows for unconstrained estimation of selectivity at larger ages, to data generated from an operating model for which the actual selectivities are flat for ages 6 and above for the NEFSC surveys and ages 5 and above for the commercial fishery.

	True	Estimated		
NEFSC Survey selectivity:				
Age 7	1.00	0.97	(0.84;	1.10)
Age 8	1.00	0.86	(0.76;	0.97)
Commercial selectivity:				
Age 6	1.00	0.96	(0.83;	1.08)
Age 7	1.00	0.97	(0.73;	1.16)
Age 8	1.00	0.87	(0.68;	1.02)
$B^{sp}_{2006}/B^{sp}_{MSY}$	1.04	0.98	(0.81;	1.15)

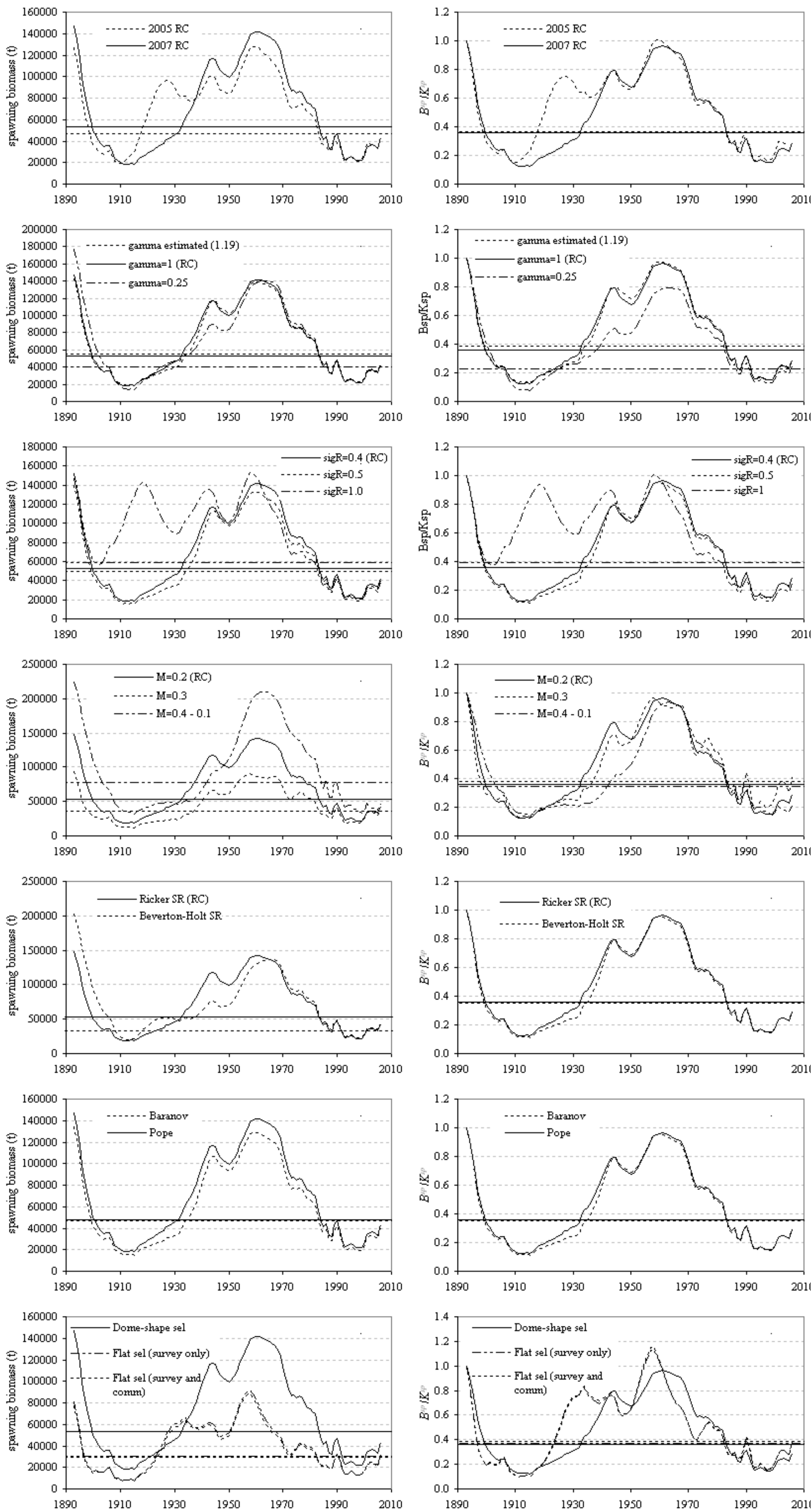


Fig. 1: Spawning biomass trajectories (in absolute terms and in terms of pre-exploitation level). The estimated B_{MSY}^{sp} and *MSYL* are also shown.

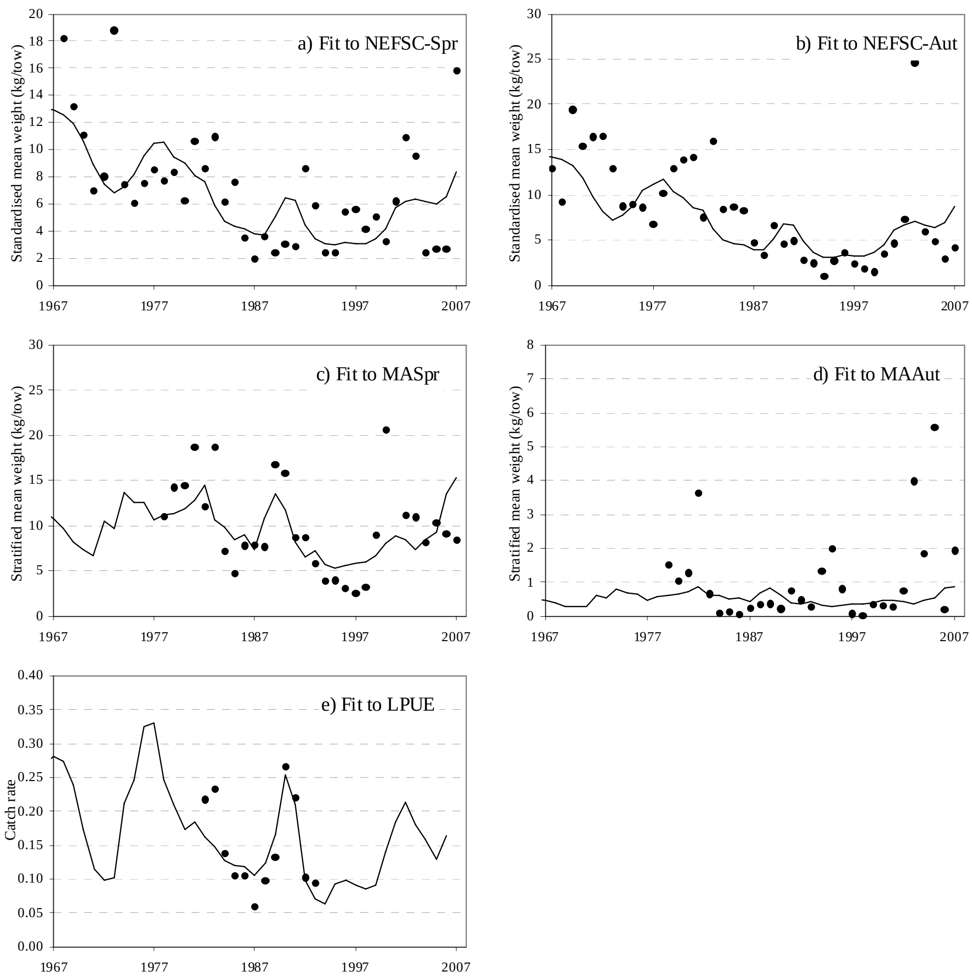


Fig. 2: 2007 Reference Case assessment model fits to the abundance indices (survey and CPUE).

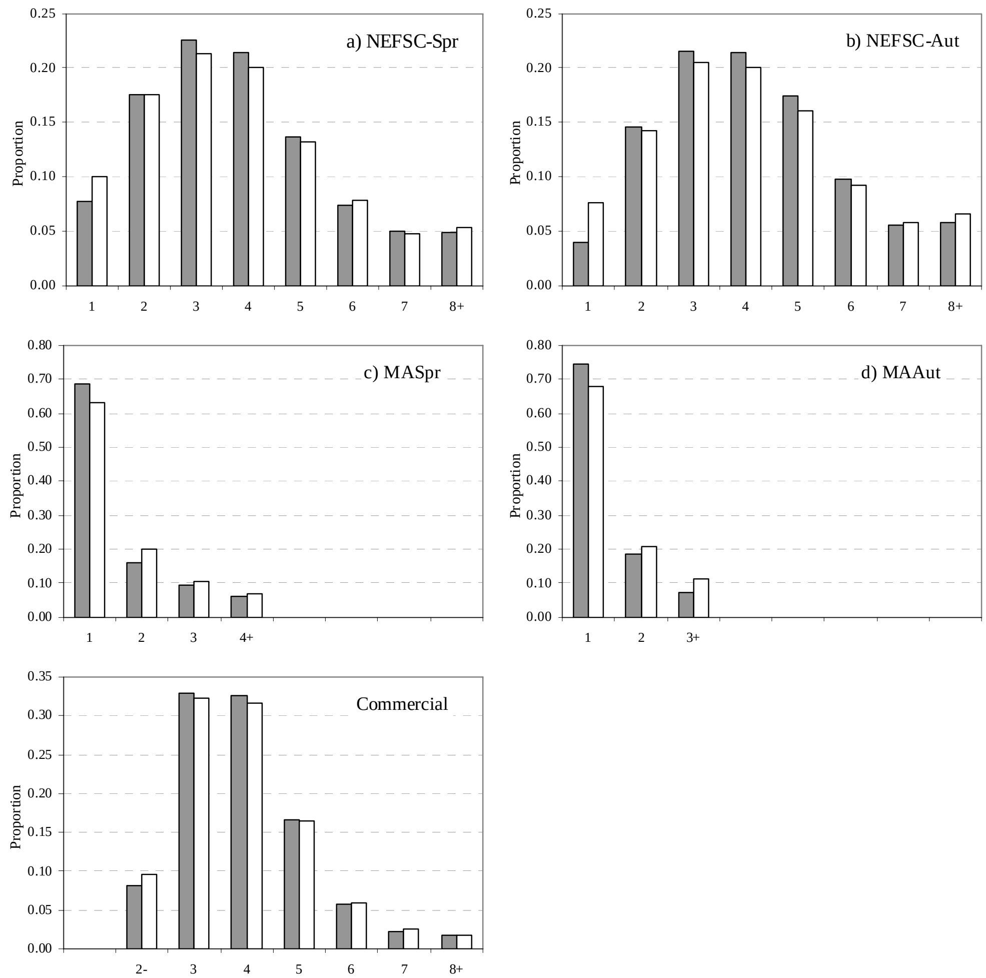


Fig. 3: 2007 Reference Case assessment model fits to the catch-at-age data (survey and commercial averaged over all the years with data for each data set). The dark bars are the data and the white bards the model estimates.

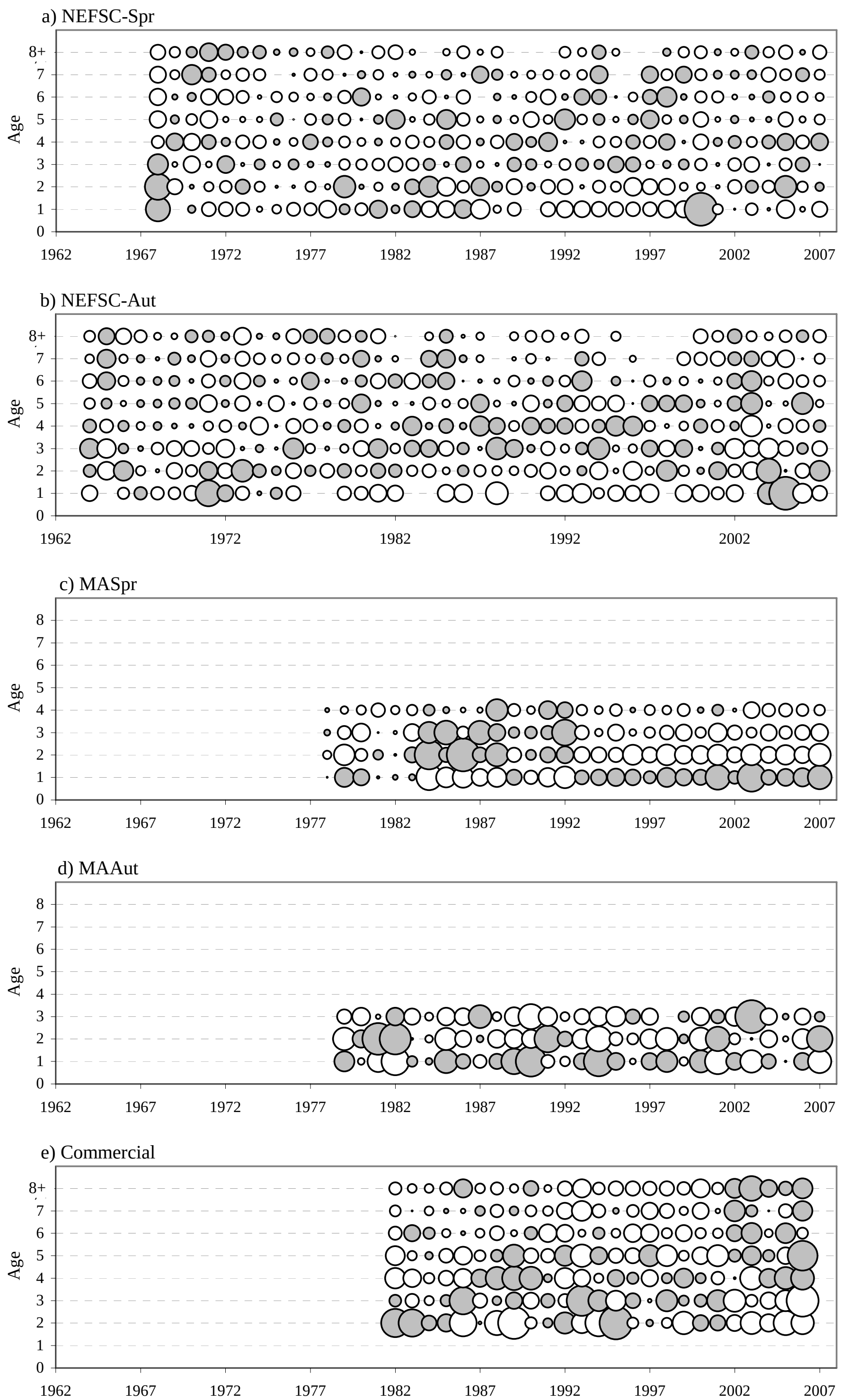


Fig. 4: Bubble plots of the standardised residuals for the catch-at-age data for the 2007 Reference Case assessment. The size (area) of the bubbles represents the size of the residuals. Grey bubbles represent positive residuals and white bubbles represent negative residuals.

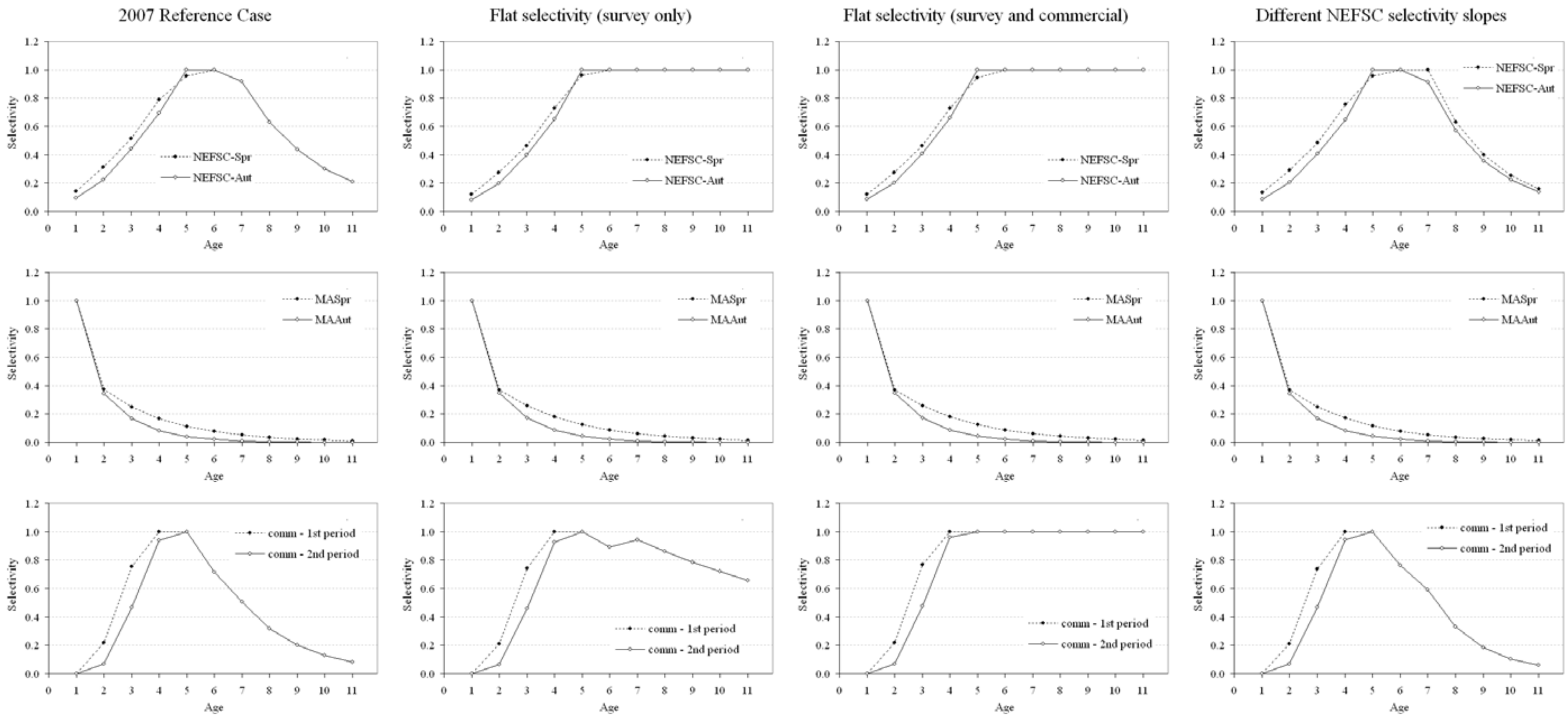


Fig 5: Survey and commercial selectivities-at-age for 2007 Reference Case and the sensitivities with flat selectivity at older ages (Sensitivities 5a and 5b), or different survey slopes for the two NEFSC surveys (Sensitivity 4).

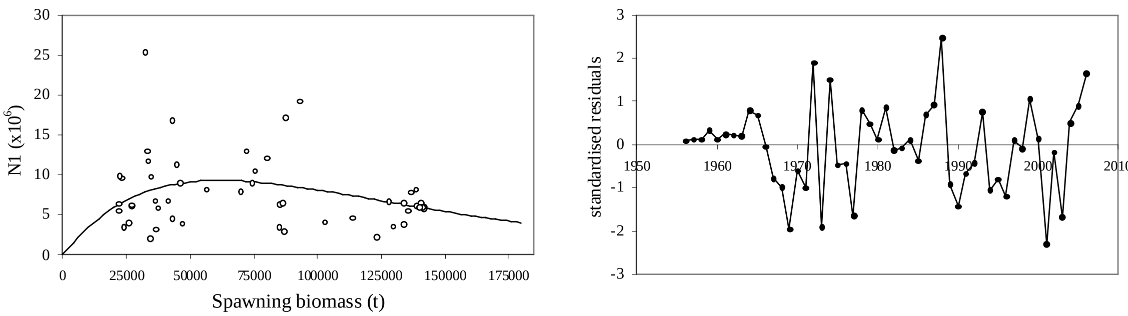


Fig. 6: The estimated stock-recruitment curve and estimated recruitments each year over the period 1956-2006 and estimated stock-recruitment residuals (ς_y) for a the 2007 Reference Case.

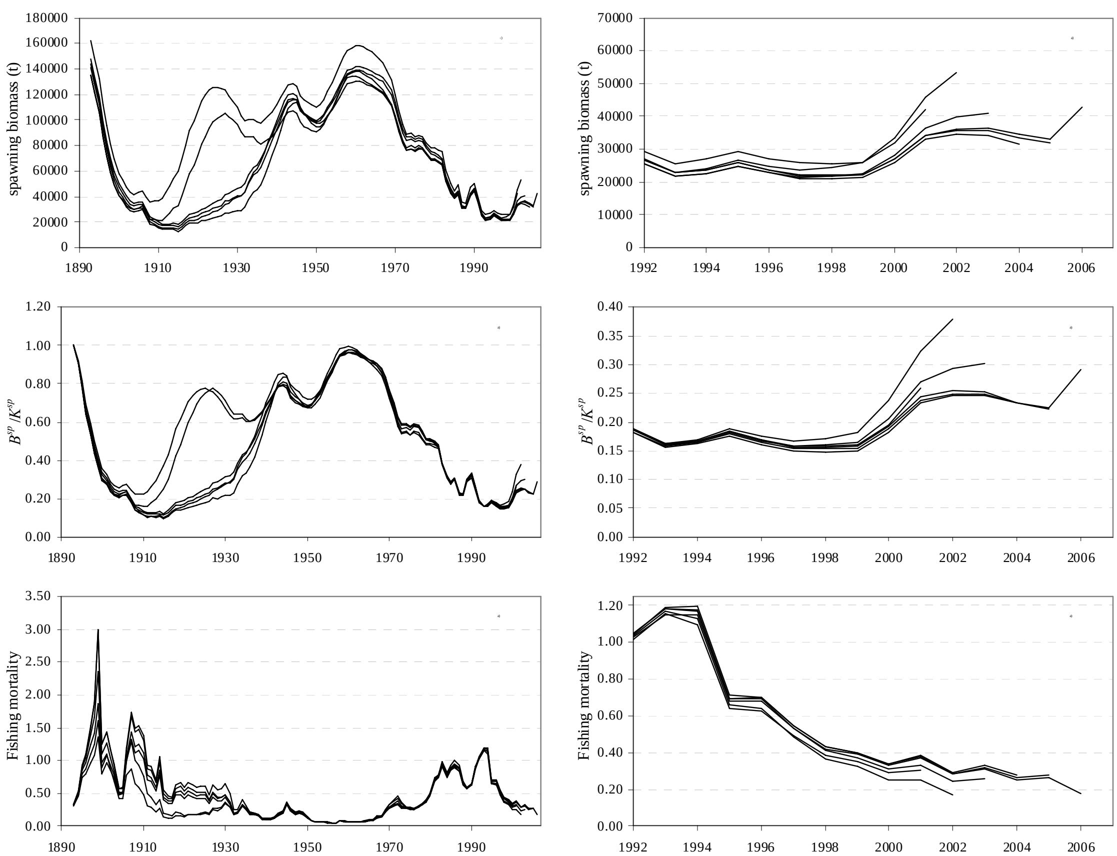


Fig. 7: Retrospective analysis of Gulf of Maine cod for the 2007 Reference Case for spawning biomass (in absolute terms, top panels, and relative to pre-exploitation levels, middle panels) and fully selected fishing mortality (lower panels).

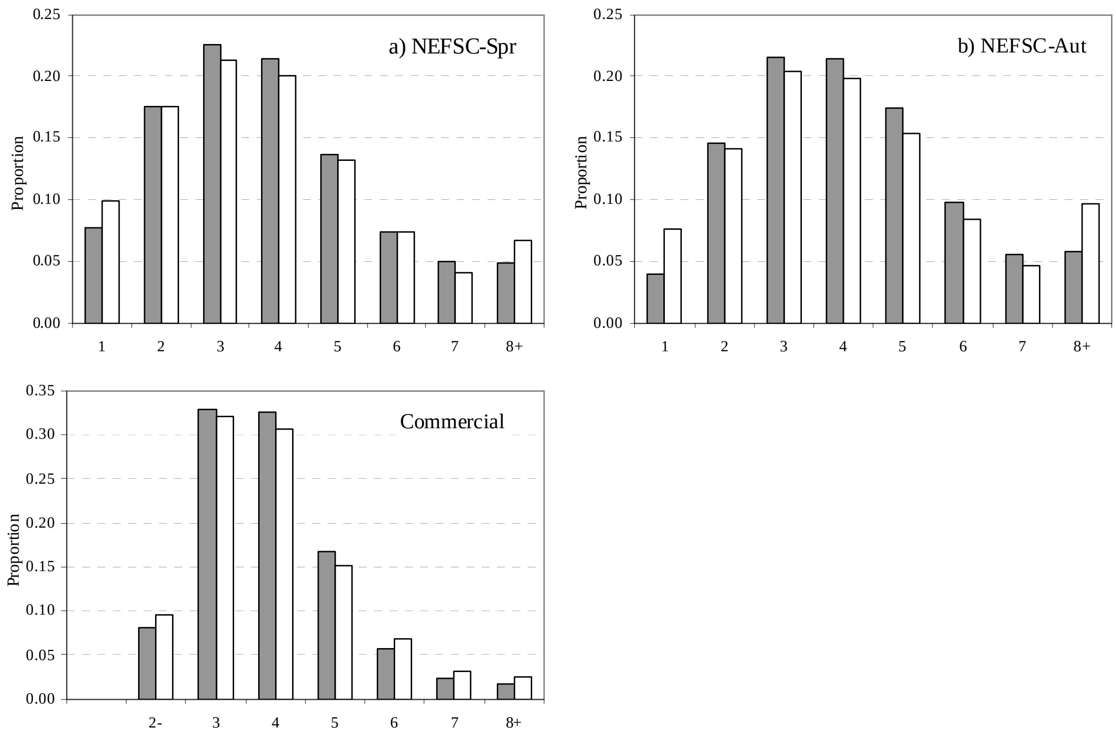
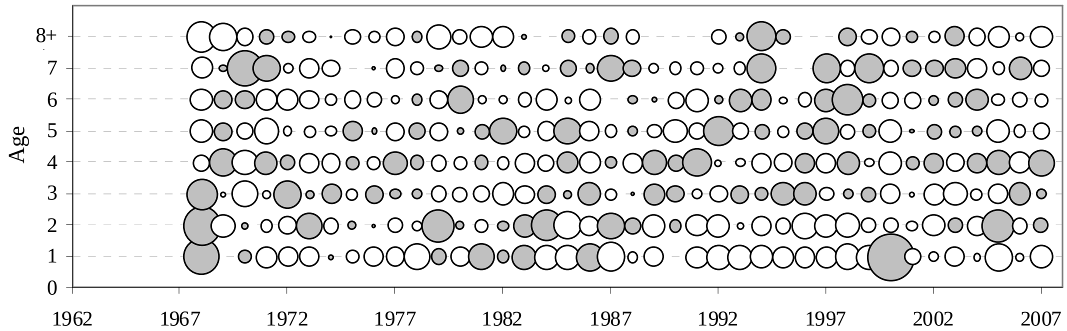
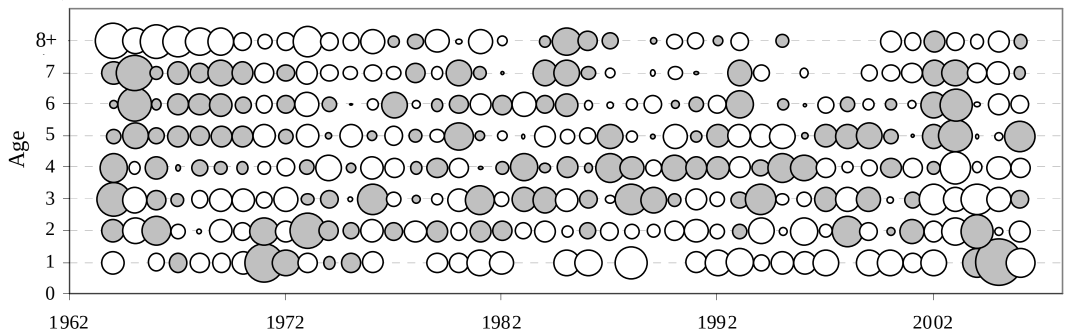


Fig. 8: Flat selectivity (NEFSC survey and commercial fishery) assessment model fits to the catch-at-age data (survey and commercial averaged over all the years with data for each data set) (Sensitivity 5b). The dark bars are the data and the white bards the model estimates.

a) NEFSC-Spr



b) NEFSC-Aut



e) Commercial

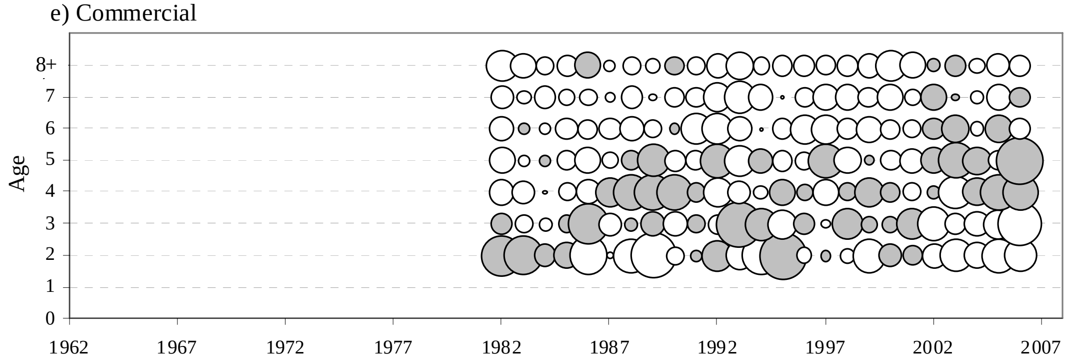


Fig. 9: Bubble plots of the standardised residuals for the catch-at-age data for sensitivity with flat commercial fishery and NEFSC survey selectivity for older ages (Sensitivity 5b). The size (area) of the bubbles represents the size of the residuals. Grey bubbles represent positive residuals and white bubbles represent negative residuals.

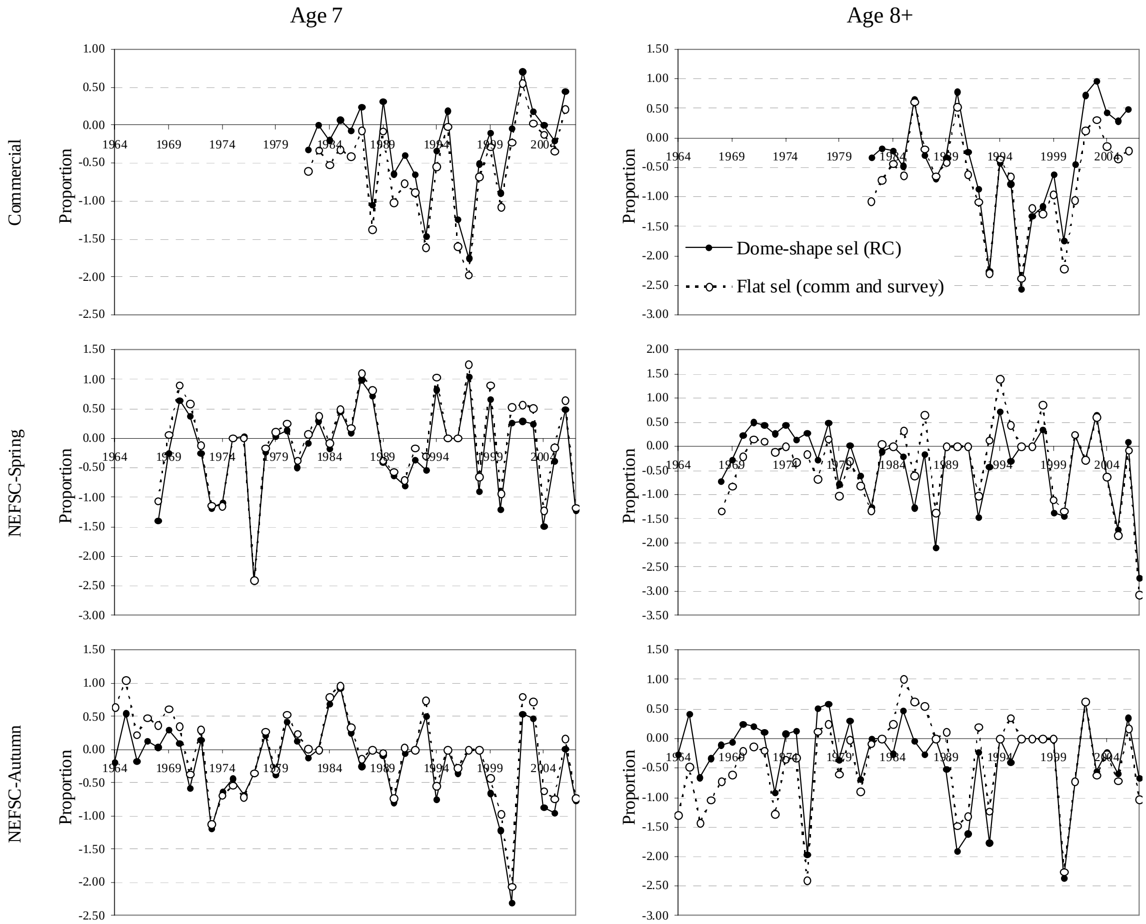


Fig. 10: Time-series of commercial and NEFSC surveys catch-at-age residuals for ages 7 and 8+, for the 2007 Reference Case with dome-shape selectivity and the sensitivity with flat selectivity for the commercial and NEFSC surveys (Sensitivity 5b).

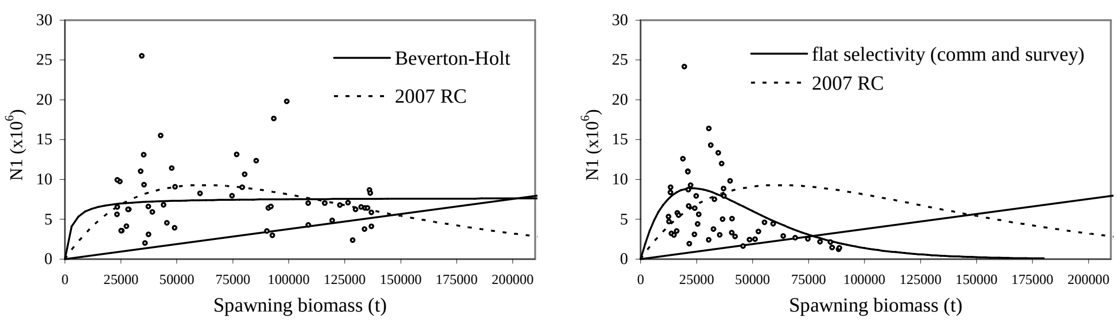


Fig. 11: The estimated stock-recruitment curve and estimated recruitments each year over the period 1956-2006 for the 2007 Reference Case and the Beverton-Holt case (σ_R=0.4) (Sensitivity 9a) and the case with flat selectivity for both commercial fishery and NEFSC surveys (Sensitivity 5b). Replacement lines are shown and intersect curves at the applicable K^{sp}.

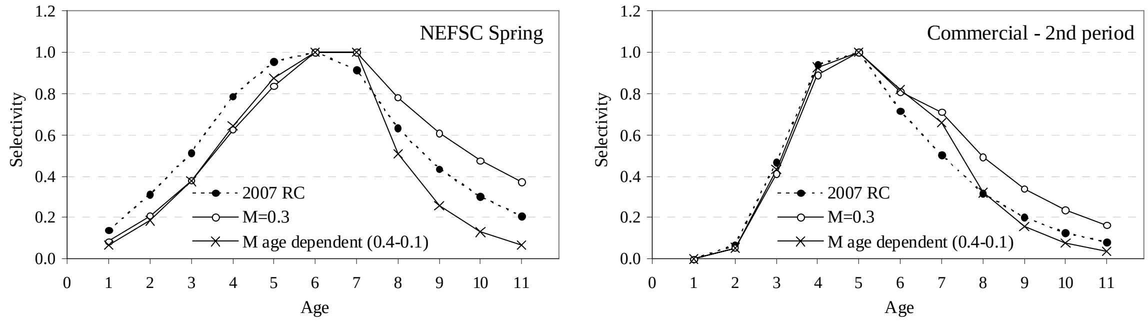


Fig 12: NEFSC spring survey and commercial (2nd period) selectivities-at-age for 2007 Reference Case and two sensitivities with different specifications for *M* (Sensitivities 6a and 6b).

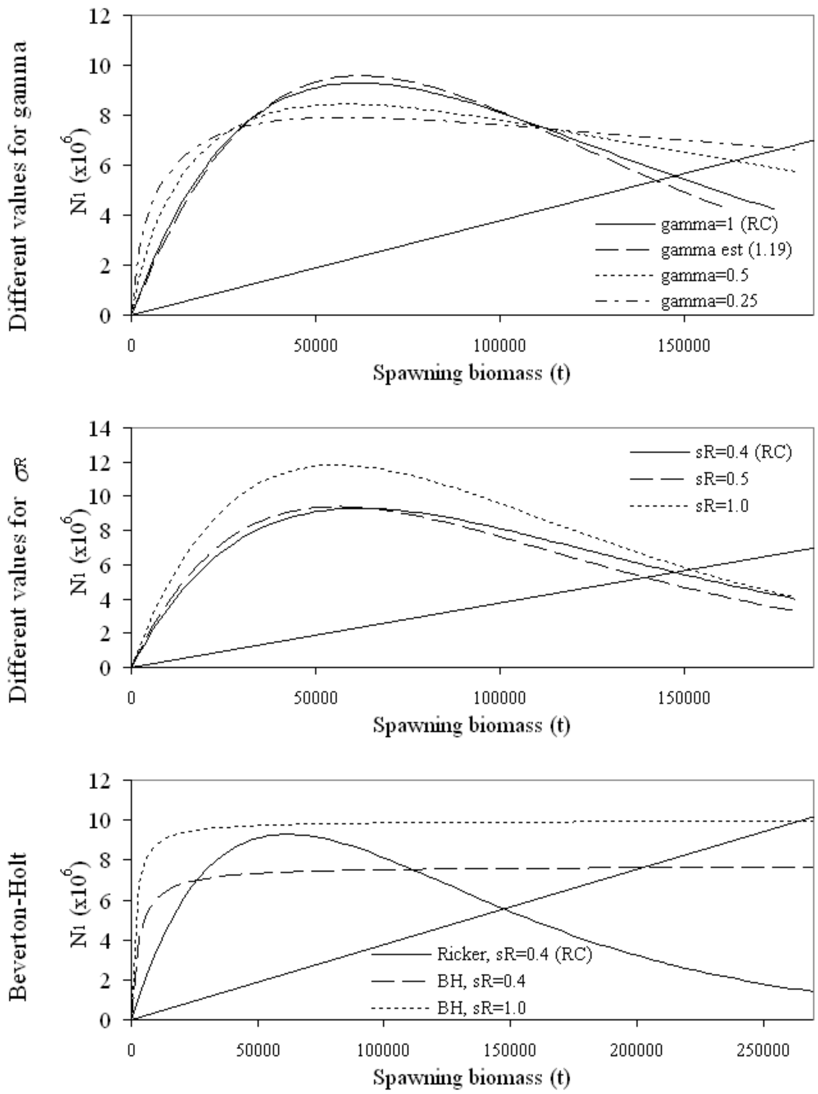


Fig. 13: The estimated stock-recruitment curve for the 2007 Reference Case and a series of sensitivities (Sensitivities 7, 8 and 9 – see Table 2). The replacement line, which intersects the stock-recruitment curve at K^{sp}, is also shown. Note the different horizontal scale for the lowest panel.

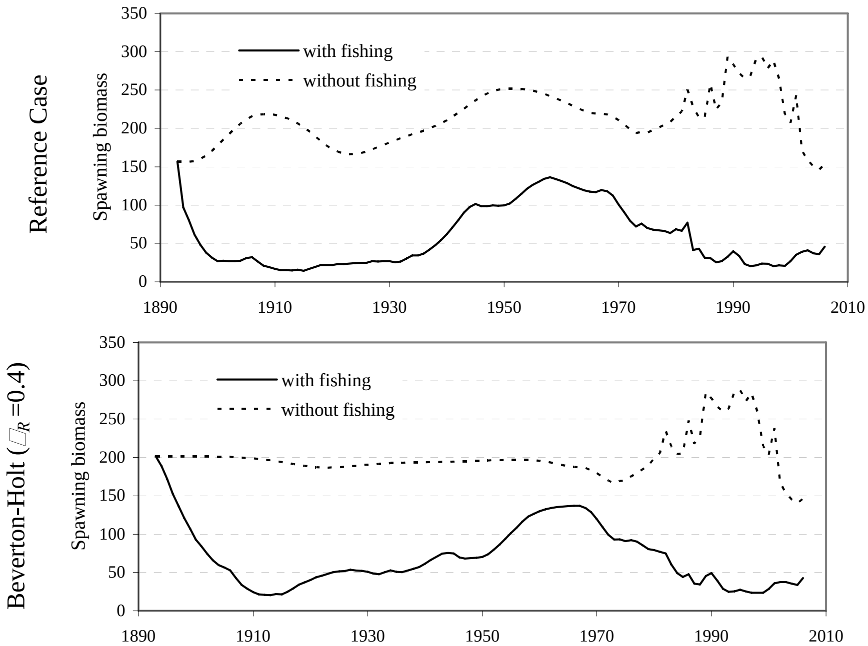


Fig. 14: Spawning biomass trajectories (units '000 tons) with and without fishing for the 2007 Reference Case and the equivalent with the Ricker replaced by the Beverton-Holt stock-recruitment function (Sensitivity 9a). Annual recruitments for the unfished cases are maintained at the same levels as estimated when fishing occurred.

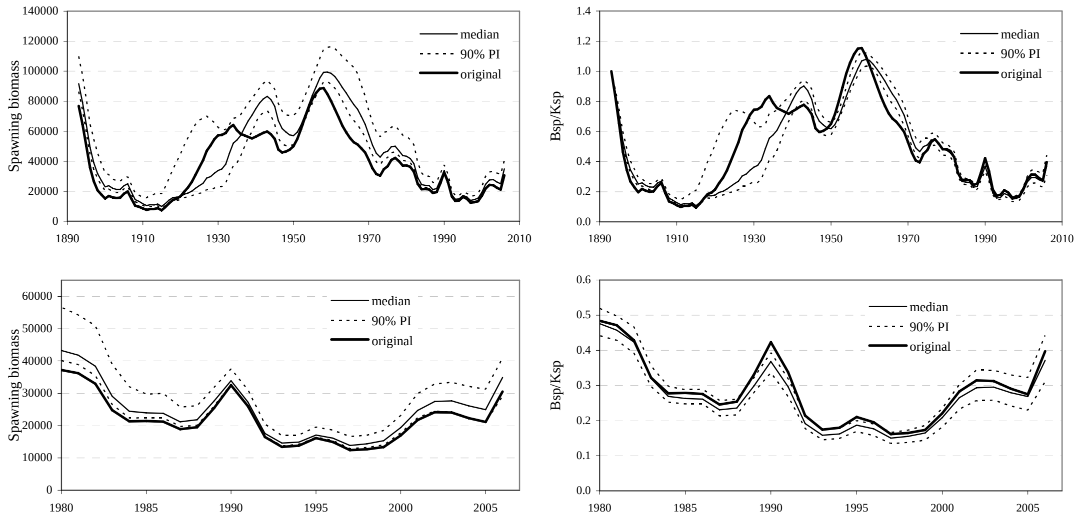


Fig. 15. Median and 90% PI's for distributions of estimates of spawning biomass trajectories. obtained under the application of an estimator identical to the RC assessment which allows for unconstrained estimation of selectivity at larger ages, to data generated from an operating model for which the actual selectivities are flat for ages 6 and above for the NEFSC surveys, and for ages 5 and above for the commercial fishery. The original estimates (Sensitivity 5b) are shown as thick lines.

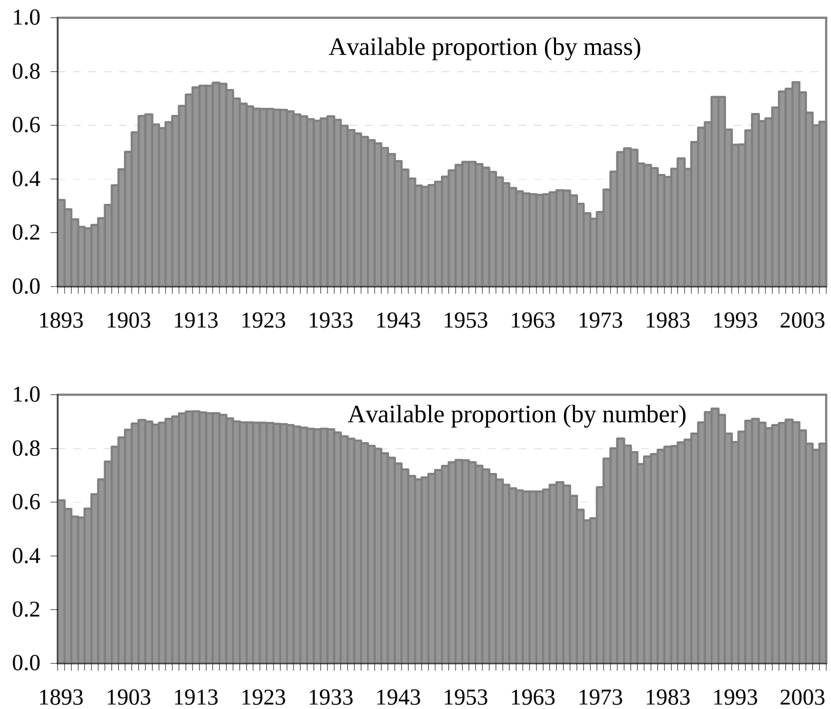


Fig. 16.These plots relates to B^{exp}, the exploitable component of the biomass in terms of the commercial selectivity. To illustrate the relative magnitude of the "cryptic" component of abundance under the 2007 Reference Case, the calculations have been performed first ignoring the downward trend in selectivity at larger ages, and then incorporating it, with the ratio shown as the available proportion.

Appendix A – Changes to the 2005 Reference Case

This Appendix details the differences between the specifications of and data input to the 2007 Reference Case assessment, and those for the 2005 Reference Case as reported in Butterworth and Rademeyer (2008a).

Updated data
Revised data as kindly provided by Ralph Mayo (NEFSC) have been used throughout to provide the new results reported here.

Additional two years' data
Butterworth and Rademeyer (2008a) used data up to 2005 only for their 2005 Reference Case assessment. A further two years' data are now available.
Commercial CAA data fitted out to age 8+ instead of 7+

Butterworth and Rademeyer (2008a) used a plus-group of age 7+ in fitting to commercial and NEFSC survey data. On this occasion, data were provided in a form which gave at-age information up to an age of 11+. Table A1 contrasts the merits of plus-grouping at different ages in relation to the numbers of ages of the commercial CAA data for which a selectivity is estimated before a continuing exponential trend to higher ages is assumed when the assessment model is fit. From the values for –lnL shown in this Table, it follows that extending the ages for which commercial selectivity is estimated from 7 to 8 is (marginally) justified on the basis of AIC – a decrease of slightly more than 1 in –lnL for the addition of one further estimable parameter. However, extending further to age 9 would not be similarly justifiable. Hence the plus group for commercial CAA data was chosen to be 8+, and consequently following S5 set equal to 1, values for S6, S7 and S8 were estimated, with a subsequent exponential decrease assumed with proportional decreases for each further age set by the estimated S8/S7 ratio.

NEFSC survey CAA data fitted out to age 8+ instead of 7+
Table A2 shows results similar to those in Table A1, but in this case for the NEFSC survey data. These indicate that, as for the commercial data, extending the ages for which NEFSC survey selectivity is estimated from 7 to 8 is well justified on the basis of AIC. The likelihood however does not improve by extending further to age 9. Consequently following S6 set equal to 1, values for S7 and S8 were estimated, with a subsequent exponential decrease assumed with proportional decreases for each further age set by the estimated S8/S7 ratio.

MA survey selectivities estimated with two parameters instead of one
In Butterworth and Rademeyer (2008a), these selectivities were assumed to decrease exponentially from age 1 (which was taken to have selectivity set equal to 1), so that a single parameter only was estimated for each of the two MA series. Examination revealed that better (and AIC justified) fits to these data were obtained by estimating S2 separately, and then assuming an exponential decrease from age 2 onwards.

Table A1: Negative log-likelihoods for potential 2007 Reference Case assessments in relation to the age at which a plus-group is formed for the commercial data, and the ages to which a separate selectivity is estimated before the assumption of an exponential trend with age for larger ages is made.

	data to 7+	data to 8+	data to 9+
estimated to 7	-4.38	9.39	
estimated to 8		8.34	30.21
estimated to 9			29.97

Table A2: Negative log-likelihoods for potential 2007 Reference Case assessments in relation to the age at which a plus-group is formed for the NEFSC survey data, and the ages to which a separate selectivity is estimated before the assumption of an exponential trend with age for larger ages is made.

	data to 7+	data to 8+	data to 9+
estimated to 7	-17.55	15.28	
estimated to 8		8.34	35.34
estimated to 9			35.33